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APPLICATION PRINCIPLES FOR MULTICOLORED DISPLAYS

A Workshop Report

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A Workshop Report

JoAnn S. Kinney and Beverly Messick Huey, Editors

Committee on Human Factors
Commission on Behavioral and Social Sciences and Education
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Foreword

The Committee on Human Factors was established in October 1980 by the Commission on Behavioral and Social Sciences and Education of the National Research Council. The committee is sponsored by the Office of Naval Research, the Air Force Office of Scientific Research, the Army Research Institute for the Behavioral and Social Sciences, the National Aeronautics and Space Administration, the National Science Foundation, the Air Force Armstrong Aerospace Medical Research Laboratory, the Army Advanced Systems Research Office, the Army Human Engineering Laboratory, the Federal Aviation Administration, and the Nuclear Regulatory Commission. The principal objectives of the committee are to provide new perspectives on theoretical and methodological issues, to identify basic research needed to expand and strengthen the scientific basis of human factors, and to attract scientists both inside and outside the field for interactive communication and performance of needed research.

Human factors issues arise in every domain in which humans interact with the products of a technological society. To perform its role effectively, the committee draws on experts from a wide range of scientific and engineering disciplines. Members of the committee include specialists in such fields as psychology, engineering, biomechanics, physiology, medicine, cognitive sciences, machine intelligence, computer sciences, sociology, education, and human factors engineering. Other disciplines are represented in the working groups, workshops, and symposia organized by the committee. Each of these disciplines contributes to the basic data, theory, and methods required to improve the scientific basis of human factors.

Preface

The Committee on Human Factors organized the Workshop on Application Principles for Multicolored Displays to examine a subset of problems associated with the current use of color in displays. Multicolored displays are used in a variety of civilian and military systems, and the rapid expansion of the field has necessitated organization, analysis, and standardization of knowledge and technical developments from diverse fields. A great number of complex, interacting factors determine the effectiveness of a color display system. Although many of these factors characterize visual displays in general, many others are specifically related to the production and use of color. The latter include both human visual-perceptual factors and color display hardware characteristics that cannot reasonably be treated in isolation.

There is substantial evidence that people prefer color. The significantly higher sales of color television sets and color photographic film and the almost exclusive production of motion pictures in color are examples of the preference. Since color will probably be used, even demanded, in displays, whether essential or not, a high priority should be given to employing it effectively—even though multicolored displays are not necessary or advantageous for all applications. Relative to a monochrome or black and white display, multicolored displays are more expensive and complex, maintenance requirements are greater, some sacrifice of display resolution may occur, and an increased probability of human error may arise if colors are inappropriately selected or information improperly color-coded.

The number of people who are experienced in color vision, who have an understanding of hardware and software, and who can evaluate the use of color in the typically short time allocated to design is very limited. With the increasing use of and demand for color in displays, many designers are

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called on to understand and to quickly achieve technical competence in what is to them an entirely new field of knowledge, human color vision. Many phenomena are rediscovered, many design features are based on intuition only, and many technical manuals are written to explain color vision to the designer.

There is indeed a wealth of knowledge scattered throughout the technical and scientific literature applicable to the use of color in displays. Much of it may be difficult to find, inappropriate, or in an unusable form. Design engineers may not trust the use of color theory for their applications to multicolored displays and color theorists may not understand the constraints imposed by the hardware or application use.

The major goals of the workshop (held in April 1985) were to bring together experts from diverse fields to share their insights, to assess the state of knowledge applicable to the use of color in displays, and to determine areas for which knowledge is incomplete and new research and development is required. In order to achieve these goals, 15 experts in display systems engineering, color perception and color, human factors engineering, industrial design, graphics engineering, and systems engineering application were invited to participate in the workshop. These specialists did not share the same background, knowledge, experience, or technical vocabulary. To faciliate communication among individuals of such diverse experience, a background paper by Dr. Harry Snyder was circulated to the workshop participants. This paper included a categorization of the correct uses of color in displays and a glossary of terms.

The introduction to this report is based on this categorization. The next three chapters address the goals of the workshop: the assessment of knowledge applicable to the use of color in displays, the identification of emerging principles, and the delineation of the research and development needs. The report should provide guidance to military and other government organizations in the development of requirements for the design, development, and operation of systems that include multicolored displays. It includes a discussion of important issues related to the behavioral aspects of multicolored display use and recommends research needed to increase the understanding and proper use of these displays in the future. However, due to the time constraints, it addresses only superficially a number of areas, such as pseudocolor coding, colors for perceptual grouping, and display dynamics.

I thank the workshop participants for the many hours they spent in preparation for and during the meeting and for their contributions to this report. The eclectic backgrounds and experience of the participants contributed to a balanced review and development of research recommendations. I thank Harry Snyder for his background paper and organization

scheme. It provided outstanding guidance and expertise for both the workshop proceedings and the report preparation.

I am particularly grateful to Stanley Deutsch for his help in organizing the workshop and to Beverly Huey for her assistance and guidance in the preparation and editing of the report. The editorial contributions of Christine McShane, the CBASSE editor, resulted in a well-organized and highly readable report.

JoAnn S. Kinney, Chair
Workshop on Application Principles
for Multicolored Displays

Contents

1
Introduction

With the increasing sophistication of both micro-electronic processing and digital computation, the use of color displays for a variety of systems and applications has increased over the past decade. Examples range from colored video games to flight simulators and computer-aided design (CAD) systems. Color is a pervasive feature of our visual world, and it follows that color should be a natural and important visual dimension in many information display applications. Color has aesthetic value, is useful in unifying spatially distributed areas, can greatly facilitate visual search performance, and can be used to enhance contrast or discrimination between adjacent areas.

One of the reasons for the proliferation of color displays is the availability of a rapidly evolving technology to support advanced display concepts. In some applications, it has been argued, color was added for the sake of technology and not for the benefit of the user. In fact, there have been a number of investigations demonstrating either no benefit from color over achromatic or monochrome displays or an actual degradation of performance due to the inappropriate use of color (e.g., Christ, 1975; Kellogg, Kennedy, and Woodruff, 1984; Krebs and Wolf, 1979).

Whether or not color is used effectively in any display depends on a number of complex, interacting factors. Although some of these factors characterize visual displays in general, many others are specifically related to the production and use of color. A three-dimensional scheme was selected to represent the multifaceted aspects of the various color display types (Figure 1-1). This scheme relates the content of the display to the assumed purpose for which color has been used in the display and to whether the display is static or dynamic.

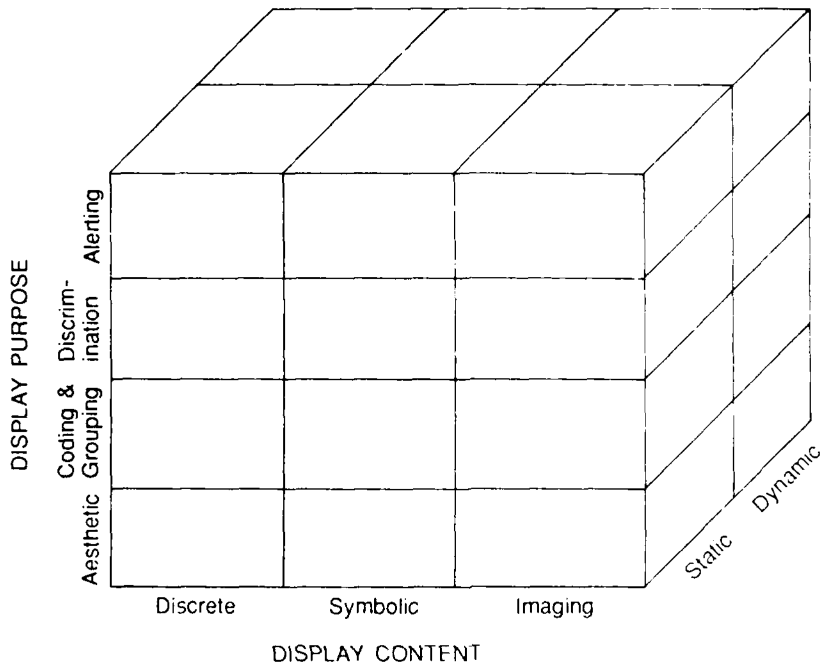

FIGURE 1-1 Three-dimensional taxonomy for color display usage.

DISPLAY CONTENT

Both chromatic and achromatic displays contain a variety of content, ranging from the simple off or on "idiot light" to the most complex motion picture film or large screen command-control display. For the purposes of this workshop, the following three types of display content seem useful to separate: discrete indicators and warning displays, symbolic presentation displays, and imaging displays.

Discrete Indicators

Color coding has stereotypically been used as a situation indicator, with green standing for safety, amber for caution or warning, and red for danger. These color codes have been applied to discrete color lights, sign fields, and vehicular instruments. Some more complex displays that use color coding for symbolic relationships have tended to avoid the use of these specific colors, reserving them for their traditional meanings. Reserving these colors limits the range of colors available to the designer in a multicolor display, a problem addressed in the workshop.

Symbolic Displays

Color coding has been used extensively for the purpose of grouping like-meaning items and separating unlike ones. In some cases, the grouping is purely symbolic; in other cases, the color coding is intended to portray both categorical differences and geometric relationships. Examples of purely symbolic use are some text-processing systems, which employ color coding to separate inserted text from original text, and command-control-communication displays, in which concepts such as friendly versus enemy, airborne versus ground, or division versus battalion versus unit may all be differentiated by color codes. In addition, however, such displays may portray the geometric (or geographic) locations of the various items in a plan view display. On occasion, certain of the geometric relationships are also color-coded.

With the advent of 10-bit image processors, the three-primary-color display has the potential for simultaneous display of 2^{30} different colors (combinations of dominant wavelength, purity, and luminance). However, successive pairs of different colors drawn from this set may not be equally distinguishable from one other. If such extensive color resolution is used for discrimination purposes, the result is wasteful and may result in operator errors.

Imaging Displays

Imaging displays range from the complex full-color, wide-screen motion picture to the simple pseudocolor-coded satellite view of a planet, and from dynamic to static modes of presentation.

Other than those imaging displays intended to duplicate our visual perception of a familiar world, there are applications of computer technology to meaningful geometric images in which color is used to code different structures, objects, distances, and the like. All such artificially created color codes have one common objective: to substitute color for some dimension of interest to the display designer and user in order to accent differences along that dimension and to facilitate natural grouping and spatial relationships. Thus, for example, pseudocolored versions of computer-aided tomography (CAT) and infrared imagery may help achieve easy discrimination of categories of objects, densities, or thermal levels.

THE PURPOSE OF COLOR IN DISPLAYS

Four categories of purpose were considered and particular display designs may serve more than one of these purposes: alerting, discrimination, grouping and categorical separation, and organization.

Alerting

The alerting function is used to warn the user that some state of a system is out of acceptable range or tolerance. Conventionally, the green-amber-red coding previously discussed is used, although this standard is often violated (for example, in nuclear power control rooms, both red and green lights are used to indicate acceptable conditions). Frequently, the degree out of tolerance is also indicated. An example is a thermometer display that changes color as the amount out of tolerance increases. On more sophisticated displays, one finds large symbols superimposed in a contrasting color to indicate a specific condition to which the operator must be sensitive and respond immediately. For example, a "breakaway X" on a military aircraft vertical situation display is a large symbol denoting that immediate action is required on the part of the pilot.

Discrimination

Under some operational conditions, color is used to improve discrimination among items on a display, by presentin ıe color symbol against another background color. As early as 1949, Chapanis suggested that the effective contrast for discrimination of one object against another is the quadratic combination of luminance *contrast* and color contrast. In more recent years, following development of quantitative systems of color measurement, researchers have explored the metrics of color contrast to yield prediction of visual discrimination between objects varying in both chrominance and luminance.

Grouping and Categorical Separation

The use of color for grouping and categorical definition of items can be beneficial to a display user. The extent to which the benefits accrue is related to a number of variables in the displayed information, such as the number of displayed items, the coded symbol legibility, and the logical relationship of the color coding to the immediate task of the user.

Aesthetic and Perceptual Organization

The most complete use of color, at least as measured by the number of different colors used exists in literal images, in which color is employed in its "natural" form to portray an equivalent photographic image in either two-dimensional or perspective view. In this application, color is used to reinforce both object separation and object/scene continuity.

One of the uses of color in dynamic, perspective imagery is found in motion pictures. Scene changes or "cuts" are often selected so that color is

used for spatial orientation and perceptual continuity. For example, regions with distinctive colors are presented first in a wide angle scene and when a cut is made to a scene with a narrower field of view, a part of that colored region is included in order to establish the location of the latter within the former. Thus, a red brick wall may be visible in the initial long shot and then be used as the colored background in the subsequent closeup, its function being to provide a perceptual bridge for the viewer and to aid rapid comprehension of the transition. Cuts are particularly important in video presentations because, with low resolution and the narrow field of view typically provided by small screens, anything that helps comprehension of the large spaces being presented by successive views is desirable. However, the degree to which color actually contributes to the parameters of the process have not been the subject of explicit research.

Artificial color can be used to substitute for natural color in an attempt to emphasize certain objects in the scene. In this application of color, usually controlled by computer, realistic colors are replaced by surrealistic colors to achieve unusual aesthetic effects. Various forms of pop art are the result of this artificial color process.

Pseudocolor is used to achieve discrimination among what would otherwise be shades of intensity in an image. For example, some satellite earth resource images indicate vegetation and water patterns in a color coding scheme that, although logical, is not related to natural colors in the same scene. Pseudocolor is also used to depict stress and temperature gradients in mechanical components designed by computer (CAD).

DISPLAY DYNAMICS

Aside from the content of a display and the purpose for introducing color, there is a third category of variables that may either enhance or compromise the use of color. This category is related to the fixed or changing nature of the display content or color. Static displays are fixed throughout the viewing period, as in color landscape slides, fixed map displays, and pseudocolored Landsat images. Dynamic displays can vary temporally to show changes in position over time. An example of the latter is a color-coded weather radar display.

2
The Current Status of Knowledge

APPLICATION OF KNOWLEDGE OF COLOR VISION

Extensive information available today about the human response to color has potential application to the design and use of multicolored displays. From Newton's discovery of the composite nature of white light to the present day, the field of color vision has attracted researchers from such diverse fields as philosophy, physics, mathematics, physiology, psychology, art, and medicine. The result has been thousands of publications and an enormous mass of data (a brief summary is included in the Appendix). Additional information is found in the proceedings of an AIC (Association Internationale de la Couleur) conference on color in computer-generated displays (Cowan, 1986).

Given this wealth of available information, one might assume that its application to the design of colored displays would be straightforward. However, a major recurring theme of the workshop was the great difficulty found in applying the existing knowledge. The reasons for this difficulty are many: they include the vast number of variables (e.g., physical, physiological, psychological, social, and contextual) that affect color perception, the many interactions among these variables, and the complexities introduced by individual differences in color vision.

The situation does not mean that generalizing from the existing data to specific applications cannot be done. There are in fact a number of specific examples (Benzschawel, 1985; Frome, 1984; Kinney, 1979; Silverstein and Merrifield, 1981, 1985; Walraven, 1984). However, the more general the attempt, the more variables that are relevant, the more exceptions to be considered, and the longer and more complicated the resulting documentation becomes. For example, the *Color Display Design Guide* (Krebs,

Wolf, and Sandvig, 1978) has 200 pages devoted to principles governing the color coding of displays and their applications. Similarly, a volume of over 300 pages was required to cover the fundamental visual, perceptual, and display system considerations for airborne applications of colored displays (Silverstein and Merrifield, 1985). In fact, one of the future research needs, discussed in Chapter 4, is a means of organizing and retrieving information from this vast array of data.

VARIABLES AFFECTING HUMAN PERFORMANCE WITH MULTICOLORED DISPLAYS

A large number of variables may affect the way an individual perceives and responds to color in displays, including physical parameters and constraints, facts concerning human color vision, and psychological effects and social considerations. The workshop participants grouped these variables under physical, psychophysical, and psychological topics. For some variables, this was relatively easy. For example, temporal stability, gamma correction, convergence, and phosphor decay are all physical in nature. However, many variables subsume two or three of these categories; even for physical variables, the aspect of concern is how the eye responds to the physical variation. All the factors that may influence perception and performance in multicolor displays are listed alphabetically in Table 2-1 (see the glossary for definitions).

Interactions Among Variables

Although the color perceived by an individual depends, to a greater or lesser extent, on each of these variables, interactions among the variables may produce unanticipated color changes. And, since much of the knowledge on color appearance was obtained under controlled experimental conditions, such as a small field, a dark surround, and precisely measured physical stimuli, these interactive effects can pose particular problems.

These complications may be illustrated by an example. The spectral composition of a source of light is obviously a prime determiner of its color appearance; however, the correlation between the spectral composition and color appearance may be destroyed if the light is, for example, too small, too dim, too far out in the peripheral field of view, or viewed under too bright or too highly colored surround conditions.

If the object is too small, its color may be incorrectly perceived even if it is of normally sufficient intensity and is foveally viewed. Not all colors are similarly affected; some suffer a much greater distortion than others. This phenomenon, called small-field tritanopia because of its similarity to that form of color defective vision, is well understood. The spectrum around 575

TABLE 2-1. Factors That May Influence Perception and Performance in Multicolor Displays

Absolute luminance	Number of colors
Adaptation level	Number of task relevant dimensions
Ambient lighting	Phospor decay
Amount of display information	Redundancy of color code resolution
Brightness	Sequence of colors
Chromaticity	Simultaneous contrast
Color coding	Size
Color contrast	Spectral bandwidth
Color induction	Proximity effects
Convergence	Spectral composition
Diffuse reflection	Spectral reflection
Foreground/background effects	Surround or background
Gamma correction	Temporal stability: additive-spatial, temporal, subtractive
Glare	Type of color performance: discrimination, recognition, identification
Layout, font, grouping	User characteristics: age, color vision anomalies, attention level, experience or practice with the display
Location in visual field: size and degree of eccentricity	
Luminance contrast	
Modulation: spatial, temporal, chromatic	

nm, normally a greenish-yellow, appears white; those spectral colors above 575 nm look yellow-red, while those below 575 nm (including the blues, violets, and yellow-greens) appear blue-green (Thomson and Wright, 1947; Weitzman and Kinney, 1967). The choice of international orange for life rafts and life vests is a direct application of the facts of small-field tritanopia; yellow, the previous choice, is confused with whitecaps when the observer is distant. However, even the specification of the critical size is subject to interactive effects of other variables. The classic limit, less than 10 to 20 minutes of arc, refers to a circular area of that diameter; this configuration results from research conducted on the phenomenon that employed optical systems to provide the monochromatic stimuli. In multicolored displays, the geometry of the visual stimulus may be different, such as an outline drawing or an alpha-numeric symbol. The critical dimensions (construction element, total area, plane angle, solid angle, stroke width) for this type of symbol are unknown. The spatial distribution and integration area are undoubtedly important and, for colored displays, the pixel count is a factor.

Individual Differences in Color Vision

A significant problem that may interfere with attempts to apply knowledge of normal color vision to multicolored displays is the extent of individual differences in color sensitivity. Many of the studies in the literature were conducted on two or three subjects. The results, while qualitatively similar between the subjects, do not allow estimates of the deviations to be found in the general population. Moreover, most of the color matching data were obtained by experimental techniques designed to eliminate the confounding effects of macular pigmentation on the matches. Large individual differences in response to metamers may be due to differing amounts of macular and lens pigmentation in the general population (Ruddock, 1972).

Another possible source of deviation among subjects is the possibility that absorption spectra of the photopigments may vary slightly from one color normal person to another. For example, Alpern and Pugh (1977) have data suggesting that differences in the maximum of the long wavelength photopigment vary over a 7 nm range. Mollon (1982) has summarized a number of studies that suggest this possibility and reviewed possible sources of error. Confirming evidence from molecular genetics was recently presented by Nathans, Piantanida, Eddy, Shaws, and Hogness (1986).

When color vision is studied in larger fields (approximately 10 degrees in diameter), individual differences are greater than those found for smaller fields. The contribution of the rods in fields of this size provides an additional source of variance, and even more complex interactions are suggested by the data of Palmer (1985). These remarks refer to color normal individuals and do not include the marked deviations known to exist in the appearance of colors to color defective individuals (see the Appendix). When more data are available for large groups of subjects, they may reveal differences of real significance for applications to multicolored displays among color normal individuals.

3
Emerging Design Principles For the Use of Color Displays

Color is being used in many modern applications to simulate the real world, to provide pleasing arrays, to provide continuity in motion pictures, or to enhance portions of the scene. The inclusion of color in a visual display is rarely obtained without additional cost. Color displays, whatever *their mode of generation*, generally cost more to purchase, maintain, and use, than do their achromatic or monochromatic counterparts. Thus the provision of color in a display should be associated with some measurable or at least definable benefit. In some applications, the benefit may be largely aesthetic or subjective, while in others it may be directly related to user and system performance. In performance-related applications, two criteria must be met: (1) the addition of color must provide some measurable improvement in performance in at least some operational conditions and (2) there must be no decrease in performance under any critical operational condition. With respect to the purposes for which color is employed in current multicolored displays (e.g., alerting the operator to some change of system status, improving discrimination among items on a display, grouping and categorical separation, and aesthetic and perceptual organization), it is important to apply color effectively so that these two performance criteria are met.

Research to date has led to a number of design principles for the use of color in displays. In this chapter we review the research and principles and provide exemplary applications.

PRINCIPLES OF COLOR APPEARANCE

The requirement that the colors perceived by the viewer are the ones intended by the display designer is basic to the use of color for any

purpose. To meet this first requirement, the desired physical stimulus (the appropriate spectral radiant power distribution) must be produced on the display and the observer must respond to this distribution as anticipated. The first requirement was a topic of concern at the workshop; the results of the discussion are summarized in Chapter 4.

The second requirement, the appearance of the physical stimulus, is the result of the processing of the physical stimulus by the human visual system. Much is known about this processing; the color appearance of different radiant power distributions under specific conditions has been extensively studied. Expectations concerning the appearance of different spectral power distributions generally stem from direct foveal viewing of the light under neutral or darkened surround conditions. However, the colors perceived by the viewer may be different from those expected by the designer due to unknown or unanticipated responses by the human visual system (see the Appendix for details).

While the delineation of adequate laws for specifying color appearances on displays requires detailed knowledge of display characteristics and purposes, generalities can be formulated from knowledge of the human visual system. The most important considerations are presented here; the reader is also referred to the Appendix for more information and references.

The most varied and highly saturated colors are perceived when the stimulus is foveally viewed and presented against a somewhat darkened surround. Too great an external illumination will cause the colors on the display to appear dark and desaturated. In addition, too highly chromatic an external illumination may cause deviations in color appearance due to chromatic induction (Benzschawel, 1985; Walraven, 1984).

The phenomenon of small-field tritanopia has been described previously. If a color is to be recognized correctly, one must be sure that it is either large enough to avoid the tritanopic effect or, if small, that it is one of the few colors (yellow-reds or blue-greens) that would not be confused.

Considerable evidence has been amassed that the blue system of color vision has poorer spatial and temporal resolution than do the red and green systems (Frome et al., 1981; Kelly, 1974). This has led some experts to discount the use of blue entirely for symbology on multicolored displays. In view of the many interactions, a more reasonable approach is to consider the application. If the information must be presented in small or brief form, it is best to use luminance or shape differences to encode it. Larger and longer symbols can be color-coded, with red-green differences being more effective than blue-yellow (Benzschawel, 1985).

If symbols on a display are to be viewed with peripheral vision, color must be used with caution. The closer to the fovea, the more likely the colors will be judged the same when they are viewed directly; the farther out,

the more likely they will be seen as white or very desaturated (Burnham, Hanes, and Bartleson, 1963; Kinney, 1979; Moreland and Cruz, 1958). The loss of color vision in the peripheral retina can be compensated, to some extent, by an increase in size (Gordon and Abramov, 1977). The increases in size that are required, however, make this an impractical solution for some purposes.

Highly saturated colors of equal luminance will often not appear equally bright. For example, monochromatic reds or blues may appear several times brighter than colors of less saturation. The phenomenon, called the Helmholtz-Kohlrausch effect, has been extensively studied and is well understood. Techniques are available to make different colors on a display appear equally bright to the human observer (Kinney, 1983; Ware and Cowan, 1984); these are described in the Appendix.

A large variation in the luminance of a colored light will often result in a change to its color appearance (the Bezold-Brucke effect). Some colors are more affected than others and the direction of the change differs in different portions of the spectrum. The general rule is that the spectral colors tend to shift in appearance toward blue and yellow as their intensity is increased. Thus yellow-reds and yellow-greens appear yellower with an increase in intensity, while violets and blue-greens appear bluer. Moreover, these hue shifts can occur when the perceived brightness of a colored light is manipulated rather than its physical intensity (Walraven, 1984).

Another change in perceived hue occurs when white light is added to colored light. This is of course a common method of obtaining a less saturated color, but it also results in hue shifts for some colors, known as the Abney effect. Desaturating a blue, for example, may cause it to appear violet. The differences, while frequently small, could be important in applications in which it is essential that the hue remain constant despite variations in saturation (Walraven, 1984).

EVALUATING THE USE OF COLOR IN DISPLAYS

For the most part, the use of color in displays has been assessed by objective methods. Thus, accuracy of response may be compared for targets of different colors or, more generally, for colored targets versus monochrome. Many ramifications are possible: color may be the only dimension in which the targets differ from nontargets, or it may be combined with other attributes such as brightness, size, and shape. The number of colors employed, the specific color set, and their contrast with the background illumination are all variables that can be manipulated.

The time required for successful visual search has figured prominently in research evaluating the effectiveness of color in displays. In it the subject searches for a specific target in an array; the time required to locate

it may be simply until the subject says "stop," identifies some distinguishing feature, or indicates success by pointing at or touching the target (Christ, 1975). Another measure used in visual search is the tendency to look at irrelevant objects, assessed objectively by the number of fixations on targets of the wrong attribute (color, size, shape, etc.) relative to those made on objects that share the defining characteristic (Williams, 1967). Again, a number of experimental manipulations are possible: An experiment by Carter and Carter (1981) provides an example. Subjects searched for a self-luminous three-digit target among other similar three-digit targets on a dark background. The variables included the number of other objects on the screen that shared the target's color, the total number of objects on the display, and the color difference between the target's color and that of the other objects. Each of the variables had a profound effect on both search time and relative fixation times.

Much of the information on the types of tasks for which color is effective in improving performance is derived from studies using these methods. For example, of the 42 studies comparing color codes and achromatic codes reviewed by Christ (1975), all used either accuracy of identification or search time as dependent measures of performance.

Subjective methods have also been used to assess color in displays. Subjects are asked to rate subjective pleasantness or personal preference for specific colors or for color versus monochrome. These methods almost universally result in support for the use of color. Subjects reported that the use of color seemed to make tasks easier and more natural. This is true whether or not there is any measurable change in performance with color (Christ, 1975; Kellogg et al., 1984).

While these objective and subjective methods have been generally successful in providing information on the use of colors in displays, a need for nontraditional measures for complex applications involving the total performance of the human-machine system was emphasized in the workshop. Color may have an impact on the total task by reducing operator workload and yet not show a measurable effect if assessed with respect to those tasks involving only the color display. For example, Krebs and Wolf (1979) found performance improvements for a combined color-coded detection and tracking task, but only when a combined performance score for both tasks was computed (Figure 3-1). The advantages of color increased with increasing task difficulty. Luder and Barber (1984) also used a multitask environment with similar results, thus emphasizing the need to assess total performance of a human-machine system in a complex task, rather than to address only the color-coded portion of the task, in order to reveal the advantages of color.

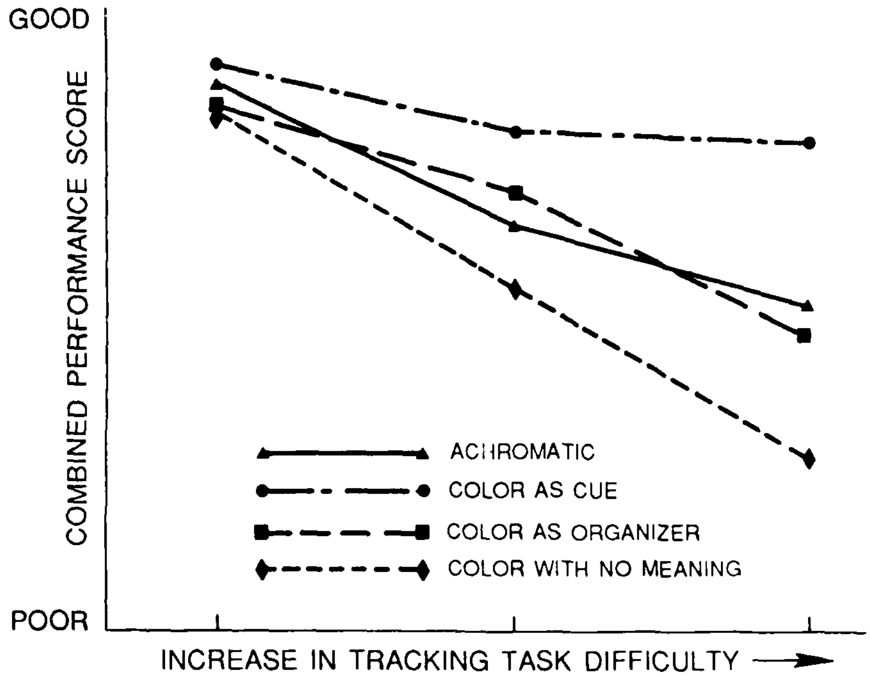

FIGURE 3-1 Effect of different methods of color coding on tracking performance. Source: Krebs and Wolf, 1979.

USE OF COLOR FOR GROUPING AND CATEGORICAL SEPARATION

Color is widely used to unify parts of the visual field. For example, this function is apparent in colored weather maps and in colored medical imagery. One of the largest effects of color found in perceptual research is the reduction of search time by color coding. This effect depends on color to unify items of the target color so that they can be scanned to the exclusion of other items on the display.

Visual search has been extensively studied, and a number of principles for the effective use of color in visual search have evolved. First, if color is to be effective in helping a viewer find a symbol on a display, the symbol's color must be known to the viewer. Without such knowledge, performance is poorer on a multicolor display than on a monochrome display (Krebs and Wolf, 1979).

Second, the advantage provided by color increases as the density or the clutter on the display increases. The principle is illustrated in Figure 3-2, which compares search times for monochrome and colored displays composed of varying numbers of symbols (Green and Anderson, 1956). In a simple uncluttered display, color contributes nothing to performance,

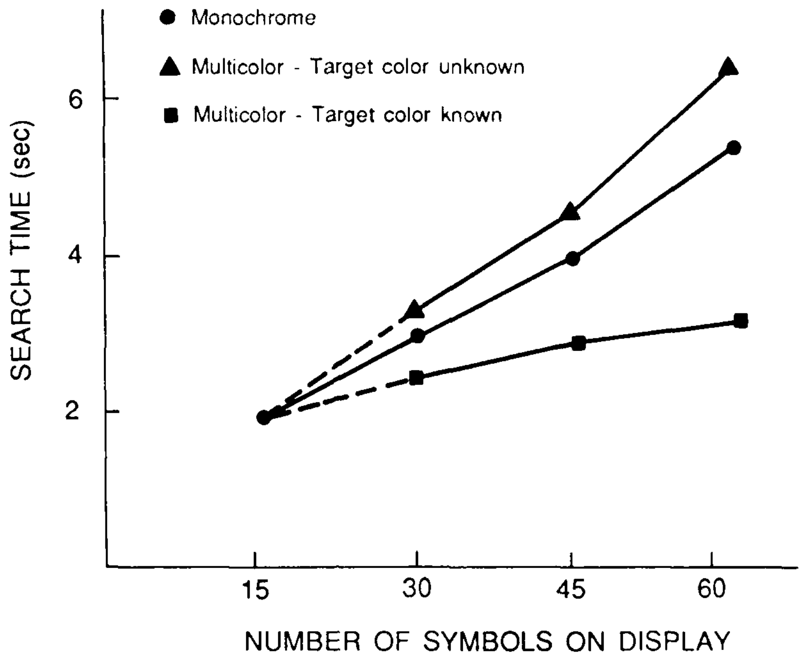

FIGURE 3-2 Effects of color coding as a function of display density. Source: Green and Anderson, 1956.

while its greatest advantage is in the display of highest density. Under appropriate conditions, the use of color can reduce search time by 90 percent in a display of 60 items (Carter, 1982).

Third, the average search time increases linearly with the number of items on the display that share the target's color, assuming again that the target's color is known to the viewer. For instance, average search time increases by about 0.13 second for each three-digit number of the target's color in the display area. The slope is steeper for more difficult targets (Williams, 1967). The linear effect of the number of items on the target's color is the most powerful determinant of search time in a colored display (Carter, 1982).

Fourth, items not of the target's color have virtually no effect on search time if their color is sufficiently dissimilar from the target's color, for example, a red and a green (Carter, 1982). Thus a display designer can avoid decrements in search performance due to nontarget colors by selecting a color code that maintains adequate separation in color space among colors. Separation or similarity of colors, one to another, can be represented by quantitative color difference formulae (see the Appendix) for this purpose (Carter and Carter, 1981; Neri, Luria, and Kobus, 1986).

Items of a color similar to the target's color (i.e., a red and a red-orange) will have a deleterious effect on search time. This effect is additive to that of same target-colored items: formulae predicting search time can have separate additive terms combining the contributions of target-colored and other-colored items on the display. The coefficients of other-colored items will be zero for colors far removed from the target color in a uniform color space (Williams, 1967).

Similar conclusions have been reached in another study (Neri, Jacobsen, and Luria, 1985). A matching task was used to evaluate performance with 10 different sets of 7 colors each. The larger the color difference between the most similar colors in a set, the shorter the reaction time and the fewer errors made on the color matching task.

One of the most effective applications of color in displays is to organize or to unify different parts of the visual field. It is used in color weather maps, color medical imagery, computer-enhanced pictures, and many other applications. One of the pronounced and most useful results of perceptual research is the reduction in search time achieved by the use of color coding. This effect depends on color to unify items of the target, so that they can be scanned to the exclusion of other items in the display. Color is a useful cue for doing a fast, simple, initial parsing of the visual field. This facility may stem from the fact that color information is one of the first attributes to be extracted in processing the visual image. Since there are few restrictions on the choice of colors, sometimes color is used simply because it is available. The more colors, the better is a common philosophy, although it is an uneconomic and untested solution.

The use of color for organizing data is an application for which there is a great need. For example, Earth Observational Remote Sensing Systems generate an overwhelming amount of data. The Landsat system in its first generation configuration produced frames of imagery that contained approximately 7.5 million pixels in each of four spectral bands. These have been produced continuously since 1972. A downlink data rate of about 30 megabits/second is needed to deliver those data to earth. In the second generation system, the spatial resolution has more than doubled and the spectral bands increased from four to seven, requiring a data rate of 85 megabits/second. Future systems being planned will involve many more spectral bands and substantial increases in the complexity of data. A significant problem in the field has been how people can successfully make use of such a volume of data. The issue is much more complex than the interface with the imagery itself, because a given data set consists of seven interrelated images in different spectral bands. Furthermore, the use of such data might involve, for example, merging newly collected Landsat data with existing geographic information expressed in visual imagery.

Color, by its very nature, seems to contain an answer to this interfacing problem. Colors exist in a three-dimensional volume of hue, brightness, and saturation, allowing relationships among data to be expressed in a variety of color schemes that could not be done in a single dimension of monochrome. Furthermore, color space is not essentially isotropic: it has significant internal structure. The achromatic axis is special, as are the red-green and yellow-blue axes. There is an increasing amount of imagery that is inherently multidimensional, such as in the multiband Landsat, and it is natural to display it in color, which is also multidimensional.

Despite the apparent rationality of such an approach, unanswered questions remain. For example, are there advantages to be gained by paralleling the data dimensions with intrinsic color dimensions? Insofar as an a priori metric can be established in the original data, one could try to preserve it in the metric of the color space. And insofar as meaningful axes can be established in the original data, one could try to map them onto the perceptual axes of color space. As a simple first pass, a principal components analysis could be performed on the original data, mapping the first component onto luminance, the second onto the blue-yellow axis, and the third onto the red-green axis. There is some evidence (Buchsbaum, 1987) that this is a useful way of thinking about how the human visual system decomposes natural images.

Likewise, the planes corresponding to the equilibrium hues could be used as landmarks in color displays. For example, if a variable is coded onto the range red-to-yellow, passing through orange in the middle, the perceptual consequences may be quite different than if it is coded onto the range orange-to-yellow-to-green, passing through yellow in the middle. In the first case, the end-points are poorly defined. Again, there are few data to indicate the usefulness of this or other approaches for choosing colors to organize multidimensional data.

Other unanswered questions concern the choice and the number of colors to be used in displays of this type. There is a limit to the number of colors that can be employed and still retain their advantage over monochrome to organize the data and make them more comprehensible. Evidence that this number is small and suggestions for the choice of colors themselves are discussed in the section below on specific colors to be used for coding. In the Landsat observation, the limit may be approached or exceeded in the future generation systems; for example, one current prototype has 128 spectral bands. Another problem stems from the limited number of hues, intensities, and saturations that can be discriminated absolutely.

COLOR AS AN AID TO DISCRIMINATION

Color, to the extent that it provides contrast, has been shown to improve the discrimination among items on a display. To assess the degree of discrimination, some means of measuring or specifying the amount of contrast among colors is required. Several studies have measured color contrast (between equally bright or equally luminant colors) by determining the equivalent luminous contrast. For example, acuity was used as the dependent variable in one study; the amount of luminance contrast was found that produced the same letter acuity as achieved with letters formed by hues of equal brightness (Eastman Kodak, 1944). In another study, apparent contrast between equally bright color pairs was measured by asking subjects to compare the appearance of color differences to luminance differences (Post, Costanza, and Lippert, 1982; Snyder, 1982). In a third type of study, the perception of a minimum border between two colored fields was measured, either by comparison to a border formed by luminance contrast (Kaiser, Herzberg, and Boynton, 1971) or by measuring the duration that a minimum boundary was visible (Frome et al., 1981).

Two conclusions can be drawn from these various studies: (1) luminance contrast is a much more effective determinant of visibility than is hue contrast and (2) hue contrast can aid discrimination, but only if the hues are widely separated in color space and there is little luminance contrast present, i.e., less than 10 percent (Lippert, Farley, Post, and Snyder, 1983). Furthermore, there is evidence that red-green contrast is more effective than yellow-blue contrast in improving visibility (Frome et al., 1981; Kaiser and Boynton, 1985; Tansley and Boynton, 1976, 1978).

THE ALERTING FUNCTION OF COLOR

In order that the alerting function be successful, several principles must be followed. First, the more sparing the use of the warning color, the more effective it is as a warning (Krebs and Wolf, 1979). This principle can be expanded to the use of a warning color on adjacent displays. For example, the use of red to map an area on one display may interfere with its alerting function on an adjacent display (Frome, 1984). The system designer must consider the whole system in choosing color codes.

Second, the colors chosen must be few in number and as discriminable from one another as possible. Krebs and Wolf (1979) suggest that no more than five colors should be used and an optimum number would be three or four. The restrictions on the number of colors employed for alerting functions stem from the attempt to eliminate errors or color confusions under as many conditions as possible. Specifications of colors for coding, such as signal lights at sea, aviation colors, and colors for traffic control,

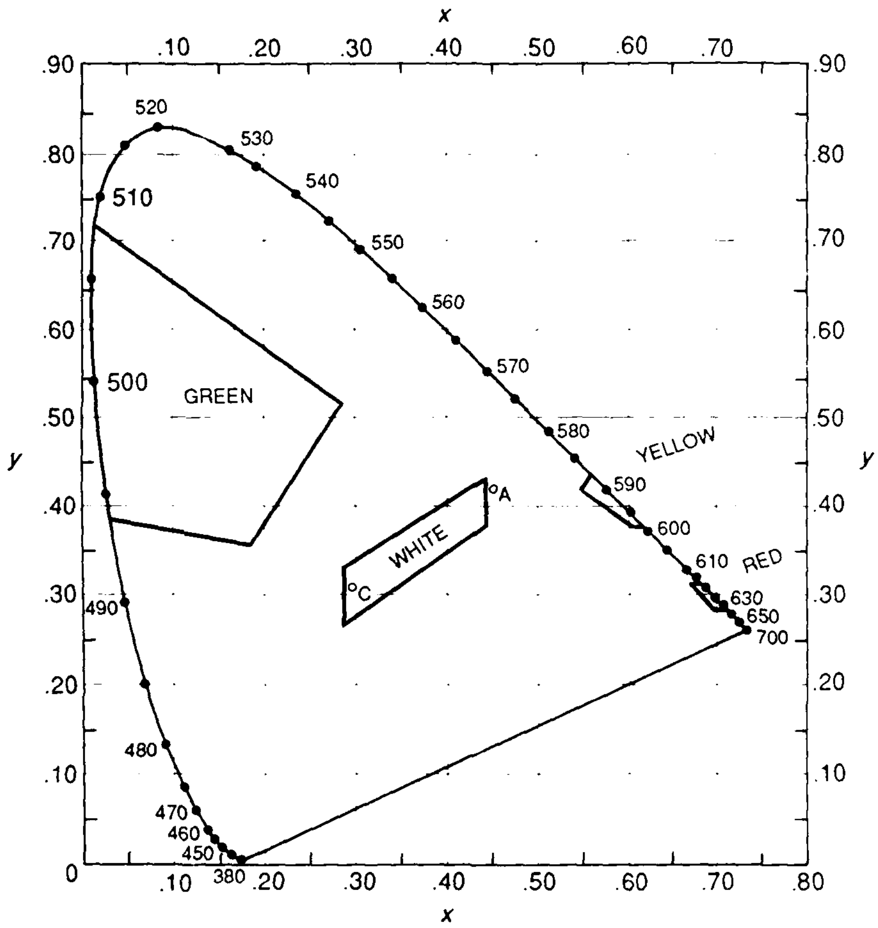

FIGURE 3-3 Recommended color boundaries for signal lights shown on the CIE chromaticity diagram. Source: Commission Internationale de l'Eclairage, 1975.

are generally available. Figure 3-3 depicts such a set of specifications, for signal lights at sea (Commission Internationale de l'Eclairage, hereafter CIE, 1975). These recommendations are being updated to include restricted specifications to minimize confusions among color defectives.

USING COLORS FOR REALISM IN COMPUTER-GENERATED IMAGERY

An increasingly popular role of color in displays is in computer-generated images. Color may be used for aesthetic purposes, as in pop art and TV advertising, or to mimic the real world, as in simulators used for military training. In either case, computer-generated images are currently very costly in terms of computer time. Major reasons for this high cost are lack of knowledge of the degree of realism required for different applications and of principles to employ color effectively to achieve this level of realism.

In some cases, the maximum photographic level of realism is not required or even desirable. Wireframe images or simple diffuse shading may be sufficient to depict the surfaces desired. Moreover, high levels of realism can actually yield diminishing returns. Added realism increases potential ambiguity; the viewer may see the wrong thing. A photographic image of a polished metal object, for instance, would include mirror-image reflections of its surroundings due to specular reflection. In such a circumstance, these superfluous reflections could distort the viewer's understanding of the geometry of the object.

An example of these unresolved problems is found in real-time flight simulation, in which there is an increasing demand for more realism. If the simulator is to be most effective, the pilot's training on it must transfer to real-world behavior. Unanswered questions abound in this area, including the degree of realism required for effective transfer of training (Jones, Hennessy, and Deutsch, 1985). Much of the terrain for a flight simulator can be modeled with only diffuse reflection, because much of the real world has a matte appearance. However, some features, such as water, pavement, and other artifacts, exhibit considerable specular reflection as well. Correct interpretation of these features may require specular information that is not generally provided in simulators. In addition, although color shading is an effective way of achieving realism and giving an impression of three dimensions, there are no guidelines to govern how many colors are needed or how many colors can be perceived by the observer. The current procedure is generally to provide physical fidelity; that is, to simulate as much as possible the physics of light reflected from the real scene. However, this can be a very costly solution.

At the workshop, several specific questions concerning the use of color to simulate reality were raised for which there are, at present, no adequate answers. They involve shaded images, the importance of highlighting and of diffuse and specular reflectance, and the dynamic use of color.

Shaded images are often used to simulate the perception of three-dimensional objects and can produce a very compelling impression of

depth. The quality of such images depends on the number of simultaneously displayed colors available and on the number of individual picture elements (pixels) in the image. Typically a computer-aided design (CAD) display of just a few years ago consisted of a raster-type cathode-ray tube (CRT) with 256-512 lines and as few as 65,000 pixels. With palettes of only 4 to 16 colors, realistic shaded images could not be produced. However, today's displays can have 1,536 lines (more than 2 million pixels) and over 1 billion colors.

The question of "how many colors will suffice?" is unanswered. The use of too few colors causes boundary artifacts to appear between colors (called *contouring*) when the objective might be a smooth imperceptible transition between colors. This objective can generally be met with 4,096 colors (4 bits per gun) or even fewer. At the other extreme, the subjective quality, called perceived realism, seems to require more colors. Some in the computer animation industry believe that full color requires 24 bits or 16.8 million colors. Some indeed claim to see improvements between 24 and 32 bit images. Others argue that 16 million colors are excessive and point out that the most demanding case would require no more than one color per pixel; 16 million colors cannot be displayed simultaneously on any current display because there are not enough pixels. It is also argued that the viewer cannot perceive that many colors. Limb, Rubinstein, and Fukunage (1977) report a maximum of about 50,000 distinguishable colors.

Other techniques are being tried to increase realism without adding additional colors. Heckbert (1982) used lookup tables for colors that were determined by their statistical distribution rather than by equal intervals in the color space. He created images with only 8 bits per pixel that compared favorably with images of 15 and even 24 bits per pixel. Pixel averaging techniques, which further mitigated contouring effects and created more effective colors without increasing memory requirements, improved images even more.

Raster displays suffer from a potential problem in that all elements must be composed entirely of horizontal line segments. The resulting stair-stepped or scalloping aberration associated with oblique lines can be mitigated by a greater raster density or by techniques involving recalculation of certain pixels (anti-aliasing algorithms). Both techniques result in higher costs. While this is not a consideration specific to multicolored displays (it occurs in monochrome as well), the question of whether there are color dependencies in these techniques should be addressed. The differential sensitivity of the eye to spatial, temporal, and orientational variations in different colors suggests that color dependencies might exist.

Another question involves the degree to which specular and diffuse reflections need to be represented in the CAD images for the perception of realism. All materials are characterized by some combination of specular

and diffuse reflection, the former being important for the perception of glossy surfaces, for three dimensionality, and quite probably in air-to-air flight simulation. However, diffuse reflection is relatively easy and inexpensive to simulate, while specular reflection requires more colors and more computer time. In addition, the simulation of specular reflection, whose luminance ranges in the real world may be 1,000 or 10,000 to 1, may require greater luminance ranges than are generally found in CRTs. The trade-offs between the expense of computing specular reflections and the perception of reality are unknown.

One recent paper was cited as addressing this point. Different pictures with different degrees of fidelity were shown to subjects who were asked to rate them for realistic appearance. The minimum number of pixels required for faithfulness of the perception in a sphere was derived from the results (Atherton and Caporeal, 1985). This technique in human evaluation of image quality may prove useful in answering other questions about the simulation of reality.

The relationship between color and the perception of motion is another issue in the simulation of reality. One important function of color in the perception of the world is to indicate, in a normally cluttered environment, which parts of the field of view belong together and will move together. Size, motion, and color all interact together in object segregation, and the color effects on perceived organization can be substantial, as is indicated by the Ishihara color vision tests and by numerous search investigations. There have been few experiments dealing with the effect of color in organizing moving arrays, and, paradoxically, color does not seem to be a prime determinant of perceived motion. For example, apparent motion can occur between different colors, rather than the same color, when the configuration allows for either perception (Johansson, 1950; Ramachandran and Gregory, 1978). An analysis of the functions that color does serve in segregating still and moving objects from their surrounds and backgrounds is necessary.

THE CHOICE OF COLORS

The seemingly simple question of which colors should be used on a multicolor display is fraught with complications and unanswered questions. It is essential to know beforehand the purpose for which the display is to be used. A simple alerting function requires fewer and different colors from those needed to simulate reality. In selecting color for coding purposes, questions concerning specific colors, number of colors, and possibilities of color continua for continuous quantities in a display must all be addressed.

Specific Colors to be Used for Coding

The theoretical and practical limits to the number of categorically different colors that can be employed are based on information available for surface colors, rather than emissive ones. It was suggested at the workshop that there is still much to be learned from the study of surface colors. For example, the mechanism of color constancy, which allows these colors to remain remarkably stable despite changes in the spectral character of the illuminant, is an important aspect of the perception of surface colors. A number of differences in the perception of surface colors and emissive colors may affect the use of color for coding. Video displays allow both the illusion of surface colors and the perception of disembodied colors floating on the face of the screen or superimposed on the real scene.

From a survey of the literature on naming of surface colors, three lines of converging evidence were discussed indicating that the upper limit of surface colors that can be employed without error in the ideal condition is exactly 11. That is, there is a potential set of 11 real reflecting colors that, under appropriate viewing conditions, will never be confused by people with normal color vision. The first type of evidence comes from color names. Evans (1948) cites a study of word counts of 17 most popular colors in that era. Of 4,416 color terms used, 4,081 (92 percent) were accounted for by 12 names (white, black, blue, red, gray, green, brown, gold, yellow, pink, silver, and purple). Similarly, Chapanis (1965) describes an experiment in which subjects were asked to select, from a large array of Munsell chips, those that were the best examples of a variety of color names. Consistent selections were made for white, gray, and black and for orange, yellow, red, green, and blue. Purple and violet were used inconsistently but a further analysis showed that these terms were used to name almost exactly the same colors. Taking this into account, the list of consistently employed names included pink and purple also.

A second line of evidence is provided by a study of confusions among colors. Halsey and Chapanis (1954) examined 342 colors of equal brightness produced by transillumination against a darker surround. A test color was presented with 171 of the others, randomly chosen, and subjects were asked to select those that "satisfactorily matched" each standard. The safest set of colors for coding, those for which there was no overlap among the confusion contours, are shown in Figure 3-4. Although color names were not employed in their study, green, yellow, red, purple, violet, blue, white, and pink are probably the best descriptors. This study shows that, if adaptation levels are controlled and only colors brighter than the surround are used, as many as eight can be employed for color coding in video displays. Because stimuli darker than the surround were not presented, gray, black, and brown could not be seen.

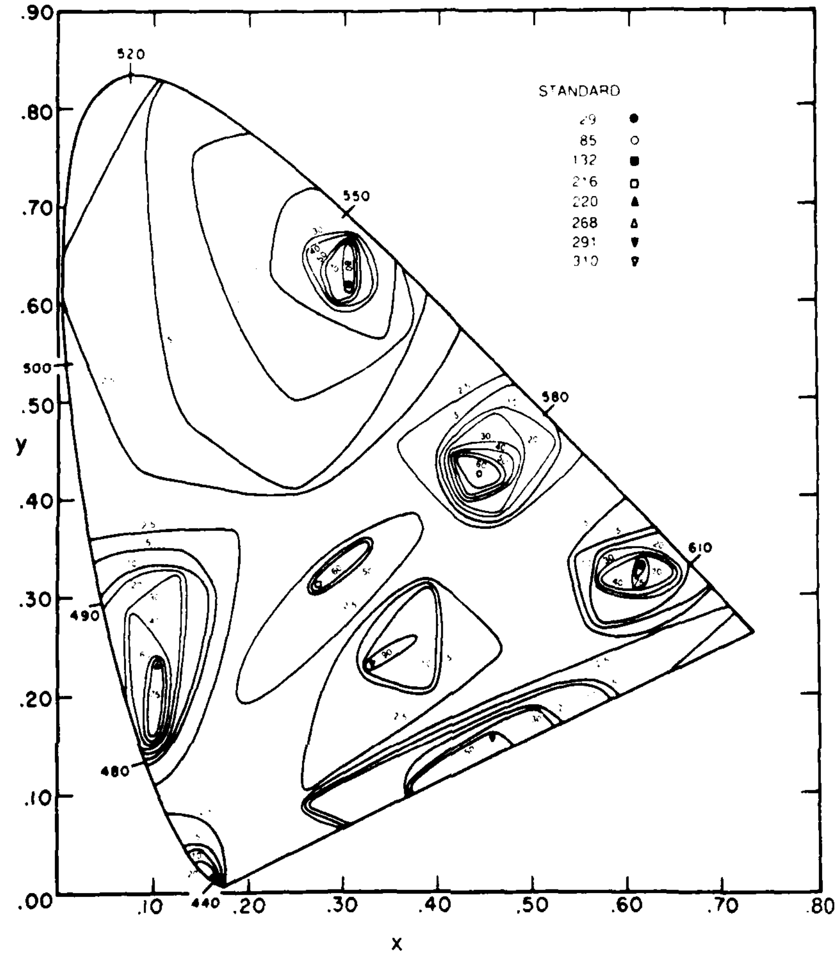

FIGURE 3-4 Confusion contours for eight standards. Each line encloses colors that were confused with the standard a given percentage of the time. Source: Halsey and Chapanis, 1954.

A different type of evidence comes from a cross-cultural study (Berlin and Kay, 1969) concluding that color names develop in a seven-stage order in the history of a given language. Figure 3-5 shows this order with the same 11 colors: black and white are the first names to evolve and the blends—purple, pink, orange, and gray—the last. In another naming study, Battig and Montague (1969) had 442 subjects write down the names of as many colors as they could think of in 30 seconds. Violet was one of the colors named. Otherwise, the 11 colors most often named first are those of the Berlin and Kay list.

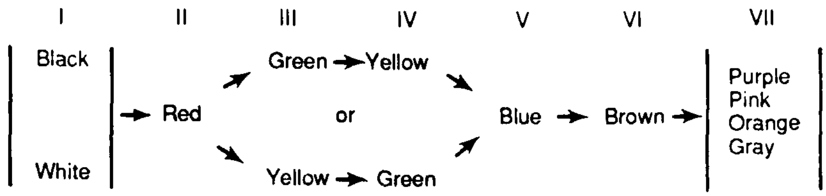

FIGURE 3-5 The order in which the use of color names have developed in language. Source: Ratliff, 1976.

The 11 colors then can be grouped as bright, unique colors (white, red, green, yellow, and blue), bright blends (orange, purple, and pink), and dark colors (gray, black, and brown). Two of the names from the word counts (gold and silver) are excluded because they are "object substance" names (Evans, 1948). The remaining names are the same as those that emerge from the cross-cultural analysis. Oddly, orange is missing from the word count list, and purple was uncommon. Perhaps this is because these colors can be completely described as combinations of red-yellow and red-blue, respectively (Fuld, Wooten, and Whalen, 1981; Sternheim and Boynton, 1966). The list thus comprises the achromatic colors, the psychologically unique colors, and three blends. The reason for the lack of a commonly accepted name for the blue-green combination is not known. While 11 colors appear to be the limit for surface colors, there are a number of reasons why the number of nonconfusable colors on a video screen is less than this limit. An important one is the requirement for reliable and consistent color production and calibration. A second reason is that color-coded characters in many video displays are almost always brighter than their background, thus eliminating brown, gray, and black. It would theoretically be possible to employ all 11 discriminable colors in the video display, particularly if it were designed to appear as a surface. To achieve this effect, the video display could be produced on a thin surface and viewed under appropriate surround conditions so that the colors changed under ambient illumination as if they were reflecting surfaces.

Additional experimental work is needed to verify and extend these speculations. It would be useful to determine the chromaticities of the 11 surfaces that, under a given illuminant, are the optimal representatives of the given color. A next step would be to alter the spectral character of the illuminance and determine for each color the best example from all possible metamers from the standpoint of resistance to color change.

Carter and Carter (1982) presented another approach to choosing specific colors to be used for coding. They used the conventional idea of color as a three-dimensional space and suggested that, if the space were perceptually uniform, then colors (represented by points in space) could

be chosen to be as far from each other as possible in this space. They had previously shown (Carter and Carter, 1981) that, as the distance between color points increases, discriminability of color codes is improved. In this conception of the problem of choosing colors, the capabilities of the display to be used are taken into account as boundaries on the achievable colors in color space. Carter and Carter offered a computerized algorithm to choose high-contrast sets of colors tailored to the capabilities of the device to be employed. The merit of this system warrants further investigation.

Color Continua

If color coding is to be used to depict spatial variation of continuous quantity, such as stress or temperature across a surface or position in depth, there are a number of possibilities for the color continuum. One could use the spectral continuum from violet, through blue, green, yellow, orange, to red; the range of perceived brightness such as white, yellow, blue, black; or a range based on color temperature, red (cooler) to blue (hotter) or on a perceived temperature as red (hot) to blue (cold).

An intuitive arrangement, using the spectral continuum, for coding three-dimensional representations was presented in the workshop, with red on top, orange as the next layer, etc. Another intuitive scheme is the use of saturation variations of a single hue to depict changes in intensity, the most intense shown as the most saturated.

In practice, pseudocolors are frequently used to depict temperature gradients. This relationship may be appropriate because of long-standing associations between color and temperature (red with warmth and blue with cold). In fact, this association between color and temperature is one of the few psychological effects of color to be replicated over the years (Payne 1964). The red-to-blue spectrum may be equally appropriate for associating most-to-least gradients in depictions of pressure and stress or, generally, any gradient of activity or potency. In studying the meaningful connotations of colors, Osgood (1971) found systematic effects of color on the judged activity or potency of the objects with which they were associated. Regardless of the object being judged, those depicted in colors toward the red end of the spectrum were judged to be more "active" or "potent" while those objects in blue were judged to be "passive." Some of these associations between color and attributes of objects may be cross-cultural (Oyama, Tanaka, and Chiba, 1962).

However, there have been very few empirical evaluations of such schemes, and in at least one the outcome was unexpected (Frome 1984). In this application, color was employed to spatially separate but relate information in a CAD display: everything on each layer of a printed wiring board was displayed in a single color. To evaluate possible color schemes,

six sets of hue/value combinations were selected and sample lines in each color were displayed to designers who were asked to specify which should be used for each layer. Surprisingly, there was good agreement that red should be the top layer, green the bottom, and aqua the interior layer. Before the study many people wrongly guessed that the designers would use intensity or brightness as the code for layer. The underlying basis for their choices is not known; one hypothesis is that the lowest level is most closely associated with the base material of the printed circuit board, which in virtually all cases is green. More research on this topic is required in order to develop a reasonable rationale for the choice of a code for color continua.

4
Research and Development Needs

The workshop participants identified a number of problems whose solutions require additional research. This chapter discusses these problems and is organized into three general topics with implications for most uses of multicolored displays, as well as three specific applications of current interest. The general topics are: (1) a method of organizing the extensive, pertinent data on color vision, (2) the requirement for reliable devices for presenting colors, and (3) an adequate system for measuring colors. The specific applications are (1) determining the colors to use for realism in computer-generated images, (2) determining the colors to use for organizing and grouping large quantities of data, and (3) determining the colors to use for coding.

ORGANIZING DATA ON COLOR VISION

There was unanimous agreement among workshop participants that there is an overwhelming need in the field for a system or framework within which to organize the vast quantities of available data so that they can readily be applied to multicolor displays. The organization must be such that knowledge can be easily understood and employed by managers, software and hardware developers, human factors specialists, and users.

The framework or system should lend itself to the conversion of quantitative data to a spectrally and spatially distributed light field in such a way that optimum perception will be achieved by the human observer. The system should define the dimensions to be considered and the significant parameters of the particular processes and their interrelationships. Establishing such a framework or system would also be useful in future assessments of the state of knowledge of the field and its research needs.

Various approaches to achieve this goal were discussed at the workshop; however, agreement was not unanimous on the best procedure. One suggestion was for the development of an expert system, a knowledge base of rules and an inference-making capability that can put the rules together to draw conclusions (Brownston, Farrell, Kant, and Martin, 1985; Prerau, 1985). The rules may be augmented by procedural knowledge. Rules take the form of:

IF (condition) . . . THEN (conclusion)

Examples of color-related rules might be:

IF (target size <z minutes AND brightness <z) THEN (do not color code)
IF (two adjacent areas have same brightness), THEN (issue caution)

Expert systems can now handle several thousand rules and will double or triple in power in the near future, so there are no technological barriers to developing an expert color system. Rather, the difficult part of building an expert system will be the acquisition of knowledge from the experts and from the literature and guidelines and the reconciliation of conflicting results. The conclusions drawn from the expert system will have to be validated against the conclusions experts draw from the same set of facts.

Some members of the workshop felt that it was premature to codify the data of color vision into an expert system prior to developing a rational framework for the data. Others felt the need for a theoretical framework to help organize the empirical one assumed by the expert system.

Another method of achieving the goal of organizing the data on color vision is to develop an adequate model of color vision based on the physiology of the human eye. Boynton (1983) has suggested a system of colorimetry and photometry based on cone excitations, and his system is described as an example of this approach. Actual values for the cone action spectra are derived from the consensus of current scientific thought (Smith and Pokorny, 1972, 1974). Three different kinds of cone photoreceptors, whose maximum sensitivity is in the long (L), medium (M), and short (S) wavelengths, absorb the radiant energy and their output is transformed into two opponent color signals and one luminance signal. The initial cone signals are all positive. Signals from the M cones are both added and subtracted from L cones. The summated signals give luminance and the difference signal is interpreted at a higher stage of processing as red, if positive, and green, if negative. Another opponent system, the yellow-blue, receives an amplified negative signal from the S cones and a positive signal from the summated L + M cones. The model is depicted in Figure 4-1.

The model is useful in describing a number of phenomena of color vision, such as additivity of luminance, the shape of the flicker photometric luminous efficiency function, and the differing brightness/luminance ratios

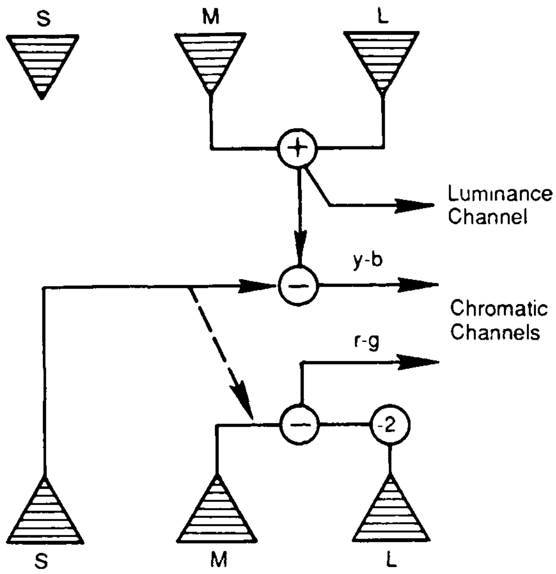

FIGURE 4-1 Boynton's model of color vision. Source: Boynton, 1979.

observed in different parts of the spectrum. A two-dimensional chromaticity diagram based on the model can be used to measure color; this diagram preserves the advantages of the CIE diagram while allowing one a better conceptualization of color appearance from the geometrical relationships (Boynton, 1986). The model also predicts a number of color phenomena of interest to color display designers. For example, the blue-yellow system contributes only a little to the perception of borders, and employing equal quantities or bits of red, green, and blue to generate a color display may be inefficient, compared with using the more important dimensions.

Modeling is an active field in color vision today and a number of theoretically-based models are available (Bird and Massof, 1978; Guth, Massof, and Benzschawel, 1980; Ingling and Tsou, 1977; Maloney and Wandell, 1986; Massof and Bird, 1978). Evidence of the recent interest is to be found in a special feature section of JOSA A on Computational Approaches to Color Vision (Krauskopf, 1986), which includes 12 papers on the topic. Another approach covering similar interactions, including the fact that color contrast gives way to color assimilation with changes in size (see the Appendix), are being developed by Jameson (1983, 1985).

Each of the models makes precise, mathematical predictions of the human response to color stimuli and tests the predictions against data from the literature. Another possible method of testing the various models might be to attempt to build an expert system based on the formal model.

The general consensus among members of the workshop on the need for organization in the field of color vision and the benefits to be derived suggest that both expert systems and modeling be tried.

RELIABLE DEVICES FOR PRESENTING COLORS

A fundamental assumption underlying the use of color in displays is that the display device is capable of producing the desired colors reliably. This reliability includes production of the same color on different areas of the screen at the same time, on the same area at different times, from one device to another of similar gender, and from a particular display device to a totally different type of color medium.

A recurring theme during the workshop was the invalidity of this assumption of reliability in the general area of emissive displays. Evidence of the lack of reliability varies from the common experience of viewing apparently seasick news commentators on TV to the frustration of visual researchers who try to obtain the same color measurements from the same monitor from one day to the next. An even more graphic example cited in the workshop was that of two different monitors in airplane cockpits, one for the pilot and one for the copilot, that were supposed to have the same colored display. Despite the fact that the two monitors were of the same design, model number, and manufacture, their appearances often differed enough to be easily noticeable when looking from one to another, a situation that could lead to different inferences by pilot and copilot.

This lack of reliability extends to the literature. A considerable number of reported studies used uncalibrated and unmeasured CRT displays. These deficiencies in experimental design exist in the use of both color CRTs as well as the monochrome CRT displays and include studies of color coding and of basic visual contrast sensitivity.

The causes of the lack of reliability are well known and apply to the most common means of manufacturing color cathode-ray displays. The shadow-mask CRT consists of three closely spaced electron guns, a metal shadow mask with precision holes or apertures, and a three-phosphor screen. Focused electron beams emitted from each primary gun pass through the apertures in the shadow mask and impinge on phosphor dots for each corresponding color. Independent voltage control of the three guns allows independent control of the luminance of the red, green, and blue phosphors and their relative proportions in the mixture. Misalignments of the electron beam with the apertures cause changes in the perceived color.

Changes also occur because the exact alignment of the metal mask changes with varying temperature as the system warms or cools. Gamma corrections, the relationship between input voltage and output luminance,

are rarely linear and differ for the three guns. The color emitted therefore varies with the relative voltage applied to each gun. For intermonitor and intermedia comparisons, different phosphors and different configurations of gun alignments and phosphor arrangements are used, resulting in unpredictable colors.

It was noted during the workshop that better displays can be built now, and that there are a number of methods currently available for solving the problem of accurate, reliable color production. For example, internal measurement systems can be built into the monitor and ROMs (read-only memory of lookup tables) can be incorporated into the design to adjust the output of the three primary colors to given specifications. Since such additions could add to the cost of displays, a need here is not so much for information but for education of designers and for technology transfer. Manufacturers need to be convinced of the advantages of reliable color generation in emissive displays and customers need to be educated to demand better quality for those applications that require it.

In order to measure the reliability of the colors produced, measurements should be made on the screen as the observer sees it. This is difficult and rarely done, since it requires spectroradiometric measurement for greatest precision. Although theoretically one could calculate the expected display color from the known amounts of each color produced by each electron gun in the CRT, because of frequently faulty positional effects, the exact color produced is not known. One member of the workshop noted that, after writing an image at a relatively low luminance, and then subsequently writing one at a high luminance, it took over two hours to stabilize the increased output. Careful photometric and radiometric measurements showed that the fluctuations over this two-hour period were as much as 70 percent of the differences between the two luminance levels. In order to ensure drift-free and transient-free changes on the display, closed-loop photometric and radiometric measurement had to be incorporated into the display system. These were major changes and it should be noted that even minor changes in a CRT output signal can produce significant changes in the colors produced. For critical applications, extensive calibration and frequent checking for system drift are necessary. However, it is likely that in the daily operation of most CRT displays, little calibration or standardization is ever done, even in research environments.

Guidelines for proper calibration and measurement of CRTs are available. A number of organizations are presently active with the problems of measurement of color in displays; these include, in the United States, the Society for Automotive Engineers, the Inter-Society Color Council, the Electronic Industries Association, the American Society for Testing and Materials, the Society of Motion Picture and Television Engineers, the Society for Information Display, and, on the international level, TC 1-10 of the

Commission Internationale de l'Eclairage. Proper procedures can be found in documents by Cowan (1983b) and Silverstein and Merrifield (1985). For those intimidated by the extensive instrumentation and effort required, Cowan (1983a) has recently published "An Inexpensive Scheme for Calibration of a Color Monitor in Terms of CIE Standard Coordinates." The procedure employs separate measures of phosphor chromaticities, gamma corrections, gun normalization factors, and frequent visual checks to ensure that the calibration parameters continue to be correct. The latter is a very important aspect of the procedure since the visual appearance of the output is the essential reason for the calibration.

While information on how to measure and calibrate CRTs exists, there is an important gap in knowledge when we attempt to assess tolerance for the variations from proper calibration. This question of acceptable tolerances must be answered for each application separately, since a variety of trade-offs must be evaluated; small tolerances increase the cost of a display, while large tolerances can result in substantial changes in perceived hue (e.g., an intended blue color that actually appears green). Information on human sensitivity to color differences on emissive displays is incomplete.

MEASURING COLORS ON DISPLAYS

A significant problem facing the designer is how to measure or specify the colors on a display. While the physical assessment of variables, such as length or intensity, is usually straightforward, in the realm of color we are dealing not with a simple physical variable but with the response of the eye to variations in the spectroradiometric energy distribution impinging on it. Almost all of the variables discussed in the previous section become important, and a system of color measurement requires extensive understanding of how the eye works and of the complex interactions that occur between the physical stimulus and the psychophysiological response.

Various types of color measuring systems are described in the Appendix. While many have been used effectively over the years, no single system of color description has ever taken into account all of the important variables affecting color perception. Each system has its own advantages and disadvantages, and the use of multicolored emissive displays adds complications to the field of color measurement.

CIE chromaticity measures are commonly used and are adequate for many applications, allowing monitoring of changes in a specific display over time, or adjustments of two different displays to produce the same color. Since the system enables prediction of whether two physically different colors will look alike when viewed under the same conditions by an average observer, it has been used effectively for years in a number of industries, such as paint and textile manufacturing, which require precise

color measurement and specification. While a number of other systems are available and may be superior in specific instances (Seim and Valberg, 1986), the CIE system is generally considered the most reasonable choice of existing metrics for many applications (Carter and Carter, 1981; Cowan, 1983a, 1983b; Robertson, 1972; Silverstein and Merrifield, 1981, 1985).

There remain, however, a number of problems and unresolved issues. It is important to note that many of the additional complications described below derive from the fact that the system is based on trichromatic color matches rather than color appearance (how the color appears to the human eye) and does not predict the latter. The facts of color appearance suggest that the use of lightness or brightness, saturation, and hue, the latter structured around four colors (red, yellow, green, and blue), would increase the usefulness of the system for applications involving color appearance. While the use of a trichromatic measuring system may intuitively seem best to the display designer who is accustomed to dealing with three color variables, there is no linear three-variable transformation of trichromatic data that will allow prediction of color appearance (except the Hurvich-James curves) or of which colors will appear equally different from one another. Thus, whenever an application requires information on how the colors will look, for example, as red, or a red that is discriminably different from another red, additional color metrics are required. Further complications arise if one wishes to specify how discriminable two different colors will be from a third or from a background color, or if one needs to describe the appearance of a color on different colored backgrounds.

This issue also must be faced in addressing the question of tolerances (the amount of deviation from specification that is acceptable). Too small a tolerance may be difficult to achieve, drive up the cost of the display, and result in imperceptible differences to the viewer. Too large a tolerance may result in unreliable color performance and color confusions on the part of the operator. A uniform color space based on color appearance—that is, a metric in which equal numbers implied equally perceptible differences—would seem highly desirable for the specification of tolerances.

Many attempts have been made to find mathematical transformations of the CIE chromaticity system that will produce uniform scales of color appearance. Currently two systems, CIELUV and CIELAB, are recommended by the CIE for preliminary trials. Both systems start with measurement of the CIE chromaticity values and convert them by formula to lightness, hue, and saturation. These systems are described in detail in the Appendix. Both systems were designed on the basis of data collected using surface or reflecting colors. Thus, although they can be applied to emissive displays, there are at least two difficulties in the extrapolation.

In order to predict color appearance and take into account color constancy, both the CIELUV and CIELAB systems (Robertson, 1977)

make use of a neutral reference color. When dealing with surface colors, the choice is a perfect white diffuser whose Y tristimulus value is 100, since reflective colors do not reflect more than 100 percent of the incident light, except in the case of fluorescent colors. For emissive displays, the choice of a reference white is much more difficult (Carter and Carter, 1983). A number of possibilities have been suggested and used, such as equal signals in all three channels, maximum signals in all three channels, or the "brightest white" possible on the display. All can be misleading and arbitrary. The appearance of the display may depend on other objects in the room or on the ambient illumination, or the observer may never see the "white" on which the calculations are based.

A second problem stems from the fact that these systems have been designed and tested with surface colors. There have been only a few empirical tests to determine whether they work for emissive displays. In the latter case, the colors may be brighter, more saturated and may appear in the "aperture" mode rather than "surface" mode (Beck, 1972). Many of the members of the workshop believe it is a major extrapolation of data to use them for emissive displays. Hunt (1985) has suggested that the differences in color appearance from one mode to another may be large enough to require different color order systems. Moreover, the data were obtained largely from judgments of small color differences or just noticeable color differences. Another insufficiently tested extrapolation is that of effectiveness in predicting the appearance of large color differences. On a more optimistic note, at least one such test has revealed adequate predictive power for suprathreshold symbol legibility performance tests (Lippert, 1985).

Another major concern in the development of an adequate measuring system is some method of specifying the effect of the ambient illumination, both its color and its intensity, on the colors perceived on the display. Perceived chromaticities may be altered by color contrast or restored by color constancy (Hurvich, 1981; Jameson, 1985), while the effects of contrast and constancy may be to some extent independent (Brill and West 1986). Laycock (1985) has demonstrated a reduced gamut of chromaticities with increases in the ambient illumination. In addition, the effects of the raster itself, color and luminance, need to be included in the specification. Preliminary results suggest complex interactions between ambient and raster luminance on color discrimination (Jacobsen, 1986). Predictive modifications for such effects are needed for any measuring system. At present, there are a few formulae describing the effects of ambient illumination (CIE, 1985; Hunt and Pointer, 1985; Laycock, 1985; Silverstein and Merrifield, 1985); the applicability of the various formulae for predicting chromatic adaptation needs to be tested extensively.

Appendix
Summary of Knowledge of Color Vision Relevant to Displays

For the reader unfamiliar with the mass of data and theory available on human color vision, general topics relevant to the use of multicolored displays are discussed briefly below, together with recommended sources of additional information.

THE TRICHROMACY OF HUMAN COLOR VISION

Normal human color vision is trichromatic: an individual with normal color vision is able to match any color that can be seen with an appropriate mixture of three other colors, usually referred to as primaries. Frequently the three colors are spectral lights, but any three colors will do as long as they are widely spread across the color gamut. Moreover, it is possible to convert mathematically from one set of primaries to another, with appropriate formulae, and accurately predict the proportions of the new primaries required in the match. The trichromacy of vision forms the basis of most multicolored displays. It also is the basis of the widely used CIE system of color measurement and specification (Wyszecki and Stiles, 1982).

It is now generally accepted that trichromacy arises because there are three kinds of cones in the retina, each with its own photopigment. Thus different spectral energy distributions produce identical effects if lights are equally absorbed in each of the photopigments. Furthermore, since the basis of trichromacy is in the original absorption of the light, color matches remain unchanged over a wide range of experimental conditions. Recent reviews of trichromatic theory, mathematics, and physiology are found in Boynton (1979), Mollon (1982), and Wyszecki and Stiles (1982).

THE APPEARANCE OF COLORS: OPPONENT COLOR VISION

Although trichromacy is a fundamental fact of normal color vision, it predicts only which radiant energy distributions will look alike, not *how* they will look. Thus, a mixture of 535 nm and 635 nm will match 585 rm, but these lights may look green, yellow, orange, etc., depending on numerous other variables. Knowledge of the fundamental responses of hue, brightness, and saturation has a history about as long as that of trichromacy. One of the earliest discoveries of color appearance was that there are four and only four unique hues—that is, hues that look like no other and cannot be formed by combinations of the others. These four unique hues—red, yellow, green, and blue—can be paired in two sets, red-green and yellow-blue, whose mixtures are complementary or produce white, when relatively balanced. Thus, adding green light to red light first produces a desaturated green and finally, with sufficient green, a fully saturated green. The same is true of yellow and blue. In fact every color has a complementary color; that is, a color that, when mixed in the proper proportions, will result in an appearance of white.

This antagonism between the hues is also evident in the two types of color contrast, simultaneous and successive. In simultaneous contrast, a small area of color surrounded by a larger field of a different color will take on the color appearance of the complement of the larger. In successive contrast, if a colored field of light is viewed continuously for a brief time, and the eyes are then turned to a neutral (achromatic) field of light, the neutral will have the color appearance of the complementary color. A useful summary of color appearance, its theoretical basis, and illustrations are found in Hurvich (1981).

A determination of the interrelationships between trichromacy and opponent color vision has been and continues to be a major empirical and theoretical undertaking. These interrelationships are fundamental to multicolored displays as well; a vast number of applications are concerned with color appearance, althought the trichromatic production of the colors on the display does not completely determine their appearance.

COLOR CONTRAST AND COLOR CONSTANCY

The perceived color of an object or a light may change dramatically with changes either in the ambient illumination or in the colors of the surrounding objects or lights. These changes are referred to as color contrast or chromatic induction. However, as pointed out by Hurvich (1981), these changes are often artificial; that is, the stimulus situation must be carefully controlled in order to demonstrate the effects. Normally the perceived colors of objects do not change much, even with sizeable

changes in either the quantity or the quality of the illumination, a fact referred to as color constancy. Thus a green object will continue to be perceived as green in the bluish-white light of noon, the reddish light at sunset, or even in the narrow-band illuminants of Land's demonstrations (Land, 1964).

The phenomenon of color constancy has been recognized for over 100 years and its relationship to color contrast extensively studied. One of the first explanatory principles, developed by the German physiologist von Kries in 1902, has come to be known as the von Kries coefficient law. Basically, the color perceived is determined by the balance of sensitivities among the three cone photopigments; if one of the three is stimulated more than the others by an illuminant, its sensitivity is proportionally reduced and it contributes less to the balance. The amount of reduction, specified quantitatively for each of the photopigment absorptions, is inversely related to the relative strengths of activation by the energy distribution of the particular light in question (Hurvich, 1981; Jameson and Hurvich, 1972).

Generalizing from extensive data on color contrast and color constancy, Hurvich (1981) finds that color constancy is not perfect but rather is approximate, and that the von Kries formulation adequately accounts for many but not all facts of color adaptation. An example is the influence of the *size of the elements in the scene* on the color perceived; the color may vary from one similar to (assimilation) or complementary to (contrast) the surrounding field (Hurvich, 1981; Jameson, 1985). More complex formulations are thus needed and simply adding a second operation, a formula that takes into account the opponent mechanisms of color vision, to the von Kries formulation greatly improves its predictive power. It is likely that additional operations may provide even greater explanatory power of models (Daw, 1984). For example, Worthey (1985) has found that constancy holds better for illuminant shifts in the yellow-blue direction than in the red-green direction, while Brill and West (1986) suggest that better predictive power may require separate formulations for color constancy and for chromatic adaptation.

At the present time there are a number of useful models that attempt to predict changes in color appearance with chromatic adaptation. The most successful models are generally two-stage, nonlinear transformations of CIE chromaticity data (Jameson and Hurvich, 1972; Takahama, Sobagaki, and Nayatani, 1984; Werner and Walraven, 1982). The CIE Committee on Chromatic Adaptation has recently proposed a method, based on Takahama et al. (1984), for predicting which colors will look alike under different types and intensities of color adaptation. This method has interim status; that is, it is to be tried in upcoming years to determine how well it predicts color matches under differing chromatic adaptations.

Thus there is no universally accepted method yet for dealing with chromatic adaptation; in fact, the authors of the models admit their tentative status. In addition, workshop participants repeatedly cautioned against too much reliance on present-day models. Much of the material on which they are based is from experiments employing reflecting samples, and the degree to which these data may be extrapolated to emissive displays is not yet known. Since the human visual system evolved primarily to deal with reflecting objects, not emissive displays, this caution may be well advised.

DEFECTIVE COLOR VISION

Most discussions of color vision assume normal or trichromatic color vision, but a significant number of individuals differ from normal. In the Western world, nearly 10 percent of males and less than 1 percent of females have some form of color vision anomaly. Although often referred to as color-blind, most of them are not, but simply see colors differently or less vividly than color normals. The most common forms of color vision defect are anomalous trichromacy and dichromacy. The former group, trichromats, uses three colors to match all the colors they can see but require unusual amounts: more red than normal is protanomalous; more green than normal, deuteranomalous; and more blue than normal, tritanomalous. Dichromats can match all colors with only two, generally a red and a blue. Monochromats, the only true color-blind individuals, are so rare they are generally not considered in discussions of color vision.

Protanopia and deuteranopia are the common forms of dichromacy; together they are called the red-green defects and are of greatest concern to designers of colored displays, since these individuals confuse reds, greens, and yellows, as well as a number of other colors. All forms of color vision defect have been extensively studied, and from these data we know what colors each type will confuse and can even infer what colors they actually see. These data are well summarized in Judd (1943), Kinney (1971), Pokorny, Smith, Verriest, and Pinekers (1979), and in Committee on Vision (1981).

The workshop did not address the problem of color defective viewers in detail but did note that this concern can be solved in specific situations either by the selection of personnel or by the selection of colors that are not confused by individuals with the more common types of color vision deficiencies. Each solution has disadvantages: selection of personnel requires testing, invites malingering, and reduces the staffing pool; selection of colors requires strict color tolerances and reduces the number of available colors for display. The choice must be made on the basis of the specific type of application of the display.

THE PHYSIOLOGY OF COLOR VISION

There is now, after more than 100 years of research, fairly widespread agreement on the underlying basis of color vision, although a myriad of details are still being debated and actively pursued. The theory is briefly sketched here because of its potential for assisting display designers and its use in organizing the data of color vision. The theory is based on different stages of the processing of color vision as one moves from the absorption of light by the cones through the various neural interconnections of the retina and on to the cells of the visual cortex.

Converging evidence from both physiology and psychophysics finds three photopigments in human cones with overlapping spectral distributions whose peak sensitivities, when measured at the cornea, are at approximately 440 nm, 530 nm, and 560 nm. The outputs of the three types of cones are fed into fairly complicated neural organizations, some of which are opponent in nature. Thus, in one channel, activity generated in the long wavelength cones inhibits or cancels activity generated by mid-wavelength cones; this accounts for red-green antagonism. Similarly another opponent channel consists of output from the short wavelength cones, which inhibits that of the long (or mid- and long-) wavelength cones accounting for the blue-yellow antagonism. In a third channel, the outputs from the cones are added, rather than subtracted, to account for many physiological and psychophysical facts concerning additivity and the perception of brightness. Finally, there is increasing evidence of a third stage of processing, which occurs within the visual cortex and accounts for a variety of facts of color constancy and color contrast (Daw, 1984).

The existence of the three photopigments of itself accounts for trichromatic vision, while the opponent channels are the basis of the facts of color appearance. The loss of one of the photopigments is one way in which dichromatic vision may be understood; protanopes behave as though they lack the long wavelength photopigment, deuteranopes may be missing the mid-wavelength one, and tritanopes the short-wavelength one. The basis of deuteranopia has long been debated and may involve defects in the red-green channel. Additional psychophysical evidence suggests that at least some classically diagnosed dichromats have three types of cones, but the third "missing" type is much less sensitive than normal and possesses anomalous spectral sensitivity (Frome, Piantanida, and Kelly, 1982). A great deal of evidence suggests that the anomalous trichromats have three photopigments, but one of the three is abnormal in its spectral position.

There are many excellent reviews of the evidence and the theory; suggested sources are Boynton (1979), deValois (1972), Hurvich (1981), Jameson (1972) and Mollon (1982, 1983).

COLOR MEASUREMENT

Many methods of measuring color have been developed over the years. The simplest is a color atlas, actual color samples organized according to hue, brightness, and saturation; a visual match is made between the color to be specified and the closest sample in the atlas. Probably the most widely know system of this type is the Munsell notation. The Munsell system has been extensively investigated and has the advantage of quite good equal perceptual spacing among the various samples in the atlas. It also affords users knowledge of the color appearance of the unknown, since they can always look at the sample specified in the atlas. The most serious disadvantage of the system is that reflected color samples never have as high a saturation as is possible with spectral or near-spectral lights; thus there is no match possible for many of the colors we are capable of perceiving in emissive displays (Wyszecki and Stiles, 1982).

Another method is the specification by dominant wavelength and purity; these properties refer to the spectral wavelength (dominant), which, when mixed with white, would match the color sample to be specified and the relative proportions (purity) of the wavelength and the white. Again, the method affords users some idea of the color appearance of the unknown, since they presumably know the color appearance of various spectral lights. In practice, matches between color samples and mixtures of white and spectral colors are rarely made because of the elaborate equipment required, and dominant wavelength and purity are almost always found using the CIE system described below.

In 1931, the International Commission on Illumination (known by the initials CIE of its French name, Commission Internationale de l'Eclairage) established a system for specifying color that has been widely used internationally ever since. The system, a direct application of the trichromacy of vision, is based on color matching data of the average of a large group of subjects. To specify a color, one simply calculates its tristimulus values, X, Y, and Z, by integrating the spectral radiance distribution of a color sample with each of the primaries, a red (x), a green (y), and a blue (z). The formulae and methods of using them are available in many publications, such as CIE Publication #15 (1971) and in Wyszecki and Stiles (1982). The system applies strictly only to small fields of about 2 degrees in size, since the original data on which it is based were obtained with this field size. However a completely analogous system is available for larger fields (10-degree) and designated by the subscript 10.

A further simplification, the use of relative proportions of the primaries, permits a two-dimensional graphic portrayal of color known as a chromaticity diagram. If two of the three quantities are known, the third can be obtained by subtraction; thus x refers to the relative amount of

the red primary ($X/(X + Y + Z)$), and y to the relative amount of green ($Y/(X + Y + Z)$). The perimeter of the color space is represented by the solid line: the spectral colors from 400 nm to 700 nm in the curved section and the purples or mixtures of violet and red on the straight line. All colors we are capable of seeing are contained within the space, with white represented near the center of the diagram at $x = y = z = .333$. Since the CIE diagram is based on relative values, its use is restricted to measurement of chromaticity (hue and saturation), and additional information is needed to assess the brightness of a color; this aspect is discussed in the section on luminance.

The CIE chromaticity diagram has many advantages for color specification. Connecting points within the diagram predicts the results of mixing the colors depicted. Complementary colors can be found, simply by extending the line connecting a color and white to the spectrum locus; similarly dominant wavelengths and purities are assessed graphically. Since the system is so widely used, published specifications for color atlases, such as the Munsell, are available. Predictions of metamers (colors that look alike despite widely different spectral energy distributions) is a simple function of ensuring that the colors have the same tristimulus values.

There are widely recognized disadvantages to the use of the CIE system as well. First, since it is based on color matching, it does not predict color appearance. The point depicted by $x = .4$, $y = .5$, for example, under neutral conditions many appear yellow-green, as one might predict from its dominant wavelength. However it might also appear white, green, yellow, or orange depending on prior stimulation, surround conditions, and a variety of other variables.

A more serious disadvantage for many applications is that color spacing within the CIE diagram is very unequal perceptually; that is, a difference of 0.1 unit, for example, in x or y may not be perceptible in some portions of the diagram but may represent an extremely large perceived color difference in other parts of the diagram. Many applications of the use of color require some means of predicting the discriminability of two colors. The paint and textile industries, for example, need a system for specifying tolerances, that is, whether two samples or dye lots will look enough alike perceptually to be used together (Robertson, 1972). Recognition of this problem has inspired numerous systems of uniform color space, many of which were transformations, both linear and nonlinear, of the CIE chromaticity values. Each was tested empirically to determine whether it adequately predicted published data on color discrimination. Each new formulation showed improvement over the previous one, but none has ever been completely satisfactory; indeed it may never be that any single space will work effectively for all applications. Moreover, empirical tests comparing the adequacy of the newer different color measurement systems

in predicting human perception or performance have failed to show any great advantage of one over another (Carter and Carter, 1981; Lippert, 1985; Robertson, 1977; Snyder, 1982).

In 1976, the CIE recommended the use of two uniform color spaces and associated color-difference formulae (CIE 1978b; Robertson 1977). These were recommended to promote uniformity of practice pending the development of a space and formula giving substantially better correlation with visual judgments.

One of these spaces, the CIE 1976 ($L^*u^*v^*$) uniform color space, known as CIELUV, is defined as follows in terms of the CIE tristimulus value, Y, and the chromaticity values x and y:

$$L* = 116(Y/Y_n)^{1/3} - 16 \text{ for } Y/Y_n > 0.008856$$

$$L* = 903.3(Y/Y_n) \text{ for } Y/Y_n < 0.008856$$

$$U* = 13L*(U' - U'_{1n})$$

$$V* = 13L*(V' - V'^{1n})$$

$$\text{with } u' = 4x/(-2xy + 12y + 3)$$

$$v' = 9y/(-2x + 12y + 3)$$

The quantities, Y_n, u'_n, v'_n are the values Y, u', v' for a nominally white object-color stimulus. This is normally taken to be the illuminant (for example, one of the CIE standard illuminants, A or D_{65} reflected into the observer's eye by a perfect reflecting diffuser.

The CIELUV space is obtained by plotting the quantities L^*, u^*, and v^* in rectangular coordinates. The total color difference ΔE^*_{UV} between two colors is given by:

$$\Delta E*_{UV} = [(\Delta L*)^2 + (\Delta U*)^2 + (\Delta V*)^2]^{1/2}$$

where ΔL^*, ΔU^*, ΔV^* are the differences between the two colors along the L^*, U^* and V^* axes, respectively. If u' and v' are plotted in rectangular coordinates, a chromaticity diagram is obtained that is a projective transformation of the CIE (x, y) chromaticity diagram. It is known as the CIE 1976 uniform chromaticity diagram. Points that lie on a straight line in the (x, y) diagram remain straight in the (u' v') diagram and additive color mixtures can be calculated in the same way.

The other uniform color space recommended by the CIE in 1976 is CIE $L^*a^*b^*$, known as CIELAB. The quantities L^*, a^*, and b^* are also calculated from CIE chromaticity values by fairly complex, nonlinear expressions. Although this system is popular, particularly in Europe, it does not have an associated uniform chromaticity diagram and thus may be less useful for systems based on additive color mixture. With both CIELUV and CIELAB it is possible to calculate approximate correlates of the perceived attributes of lightness, hue, saturation, and perceived chroma from them (CIE 1978b; Hunt, 1978). In many industries in which small color differences have to be measured and specified, it has been found that better results can be obtained by giving different weights to the components (Clarke, McDonald, and Rigg, 1984; Robertson, 1972, 1980) and the optimum weights appear to depend on the materials measured.

For the application to emissive displays, it should be noted that most of the work on color difference formulae have been done with object colors (reflecting surfaces); extrapolating these data to colors obtained on emissive displays raises a number of questions. These are discussed in the section on research topics.

THE INTENSIVE DIMENSION OF COLOR MEASUREMENT

The measurement of light, electromagnetic, or radiant energy to which the eye is sensitive was standardized in 1924 by the CIE, and these methods have been employed internationally ever since. In the most general form, without the constants which apply to specific units, the equation for light is:

$$\int_{360}^{830} L_{e,}\lambda(V\lambda)d_{\lambda}$$

where L refers to luminance, $L_{e,}\lambda$ to spectral radiance, and $V(\lambda)$ to the spectral luminous efficiency of the human eye.

There is no doubt that for many, indeed most, applications this definition of light adequately assesses the effectiveness of the radiation for human vision. Thus different spectral radiances that have equal luminance will provide an equal stimulus for vision, will permit equal legibility of alphanumerics (Guth and Graham, 1975) and visibility of borders (Kaiser, 1971) and, in many cases, will look equally bright (CIE, 1978a). Luminances display the important property of additivity; that is, the luminances of colors of different radiometric energy distributions can be added together to correctly predict their sum; this permits the use of one number to assess the light-giving quality of any radiant energy distribution. However,

it is also true that there are other applications for which equal luminances do not give an indication of the effectiveness of the radiance for human vision; many of these are simply an outgrowth of using $V(\lambda)$ for situations in which it is not applicable, such as for mesopic or scotopic light levels or for color defective individuals. These various inappropriate uses of normal photopic measures of light were summarized by Kinney (1967, 1975) and CIE (1978a).

For the measurement of color, perhaps the most important of these problem areas is that equal luminances do not always appear equally bright. This effect has been well known for more than 30 years (Chapanis and Halsey, 1955; Dresler, 1953; Sanders and Wyszecki, 1958). Luminous efficiency functions determined by heterochromatic brightness matching are higher on the ends of the spectrum than is $V(\lambda)$ and do not display additive properties (Ikeda, Yaguehi, and Sagawa, 1982; Kaiser and Wyszecki, 1978). The implications of these facts for color theory and measurement have been pointed out by many authors (CIE, 1978a; Guth, Donley, and Marrocco, 1969; Kinney, 1975).

The lack of equivalence between luminance and brightness is a practical problem only in certain circumstances. The most highly saturated colors, particularly at the ends of the spectrum in the reds, blues, and violets, show the largest difference, appearing two to three times as bright as their luminances would suggest. As saturation is decreased the difference decreases, and for the most neutrals, whites, and off-whites, luminance and brightness can be considered equivalent for most applications. The effect is also not found in brief or flickering stimuli; $V(\lambda)$, having been determined primarily by flicker photometry, is a good measure of the effectiveness of radiant energy under these conditions. Finally, it must be pointed out that the problem occurs only if the appearance of equal brightness among colors is desired; an example might be a display of different colored lights, each of which should be equal in arousing the attention of the user.

There are easy methods of achieving equally bright colored lights. Kinney (1983) calculated a brightness-to-luminance ratio for spectral radiations based on a comparison of the luminous efficiency functions derived by heterochromatic brightness matching (CIE, 1981) and by $V(\lambda)$. Measured luminances of lights are simply multiplied by the appropriate ratio; the ratios approach 2.0 for the reds and blues and are greater for violets. The use of the ratio provides a rough estimate of the amount of luminance required to achieve equally bright appearing colors; strictly speaking it should be applied only to monochromatic lights but probably can be used without great error for highly saturated reds and blues.

A much more comprehensive solution has been provided by Ware and Cowan (1984). They assembled all the data in the literature in which heterochromatic brightness matching to a standard had been employed

and then subjected this data base to a curve-fitting procedure to find the best-fitting polynomial to describe the data. The resulting formulae, which require only the measurement of the luminance and of the CIE chromaticity coordinates of colors, can be used for colors of any chromaticity, to predict the amount of luminance needed for equally bright appearance. The conversion factor, for a color whose y chromaticity coordinate is greater than 0.02 is:

$$C = 0.256 - 0.184y - 2.527xy + 4.656x^3y + 4.657xy^4$$

Limiting conditions and a graphic solution for colors whose y value is less than 0.02 are given in Ware and Cowan (1984).

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Glossary

This section contains a glossary of visual, photometric, display hardware, and other terms. It provided a reference vocabulary for workshop participants who represent various disciplines, each of which uses its own technical terms. Other information is available in the Appendix.

Adaptation: The adjustment of the visual system to changes in luminance. Adaptation to darkness takes longer (up to 30 minutes to near asymptote) than does light adaptation (on the order of a couple minutes).

Aliasing: An artifact of inadequate sampling that causes an imperfect definition of a visible edge between two entities. The most common example is the stair-stepped aberration on a raster type CRT that otherwise is supposed to be a smooth diagonal or curved line.

Ambient Illumination: The light on the display or the working area. It is measured in illuminance units, such as foot-candles (English system) or lux (SI system).

Anti-aliasing: Techniques for smoothing the stair-stepped appearance of aliased lines or edges.

Brightness: The perceived quantity of intensity of a surface or emitter. Brightness is generally correlated with luminance, and can be affected by both purity and wavelength of a color stimulus. The term brightness is often incorrectly used interchangeably with luminance. Brightness refers to the perception, while luminance refers to a physical measurement.

Cathode-ray Tube (CRT): An electron device containing one or more electron sources such that the impinging of an electron stream on a (phosphor) surface causes luminescence, phosphorescence, or both,

resulting in an increase in luminance. The television display is a typical example. CRT displays can be in monochrome or color.

Chromaticity: The combination of excitation purity and dominant wavelength of a color. As contrasted with luminance, chromaticity is the quality of the color rather than the intensity of the color. As measured in the 1931 CIE system, chromaticity is completely defined by the x, y chromaticity coordinates.

Chromaticity Coordinates: In the 1931 CIE system, there are three coordinates which fully specify the chromaticity of a surface color or an emission from a display. Letting X, Y, and Z be the CIE tristimulus values (red, green, and blue, respectively), then the chromaticity coordinates x, y, and z are defined as:

$$x = \frac{X}{X+Y+Z};\ y = \frac{Y}{X+Y+Z};\ \text{and}\ z = \frac{Z}{X+Y+Z}$$

From the above formulae, it can be seen that $x + y + z = 1$. Thus, the chromaticity coordinates of any color are totally defined by any two of the coordinates, conventionally x and y.

Color: The characteristic appearance of an object or signal to which the adjectives red, green, blue, cyan, etc., are applied. Color has three perceptual dimensions: hue, saturation, and brightness. These are roughly correlated with the physical dimensions of dominant wavelength, excitation purity, and luminance, although the correlations are imperfect and nonorthogonal.

Contrast: Luminance contrast can be defined in several ways. Most typical are contrast ratio (L_{max}/L_{min}), luminance modulation ($[L_{max} - L_{min}]/[L_{max} + L_{min}]$), and relative contrast ($[L_{max} - L_{min}/L_{min}]$), in which L_{max} is the more luminous of two objects and L_{min} is the less luminous of the two.

Diffuse Reflection: Diffuse (literally, "scattered") reflection consists of an infinite number of rays, reflected equally in all directions, from the point of an incident ray's impingement on a surface. In perfect diffuse reflection, all reflected rays are of equal intensity. This means that any point reflecting light diffusely will appear equally bright from any viewpoint (essentially, this is why diffuse reflection is relatively inexpensive to compute. The brightness of the reflected rays varies as the cosine of the angle of incidence, measured with respect to the surface normal at the point of incidence. Thus, reflected energy will be greatest where the incident light is perpendicular to the surface (0 degrees) and least (darkest) when the incident light is tangent (90 degrees) to the surface. Assuming that the incident light is white, diffuse reflection is generally assumed to be the color of the object (see Specular Reflection).

Display: Any real surface having a luminance different from its surround. There is no limit as to its size or composition.

Dominant Wavelength: The wavelength on the spectrum locus intersected by a line drawn from the equal energy ($x = y = z$) point through a given color. Colors in the purple region are defined by their complementary color.

Emissive Display: A display that produces its own luminance, as opposed to one which requires ambient illumination to develop a luminous image.

Foveal Vision: Vision within about 1 or 2 degrees of the line of sight. The foveal, or the central part of the retina, is most sensitive to color, has the greatest spatial resolving power, and is less sensitive under low illumination conditions than is peripheral vision.

Hue: That attribute of a color to which commonly used labels, such as red, green, and blue are applied. The hue generally correlates with the dominant wavelength of a color.

Illuminance: Luminous flux per unit time falling per unit area on a surface (see Ambient Illumination).

Luminance: The luminous intensity per unit area per steradian emitted from or reflected by a surface. Luminance generally correlates with the perception of brightness. Luminance is measured in foot-Lamberts (English system) or candela/square meter (SI system), commonly called the nit.

Metamer: Lights of the same color but different spectral energy distributions.

Monochrome: Having a single dominant wavelength or hue. Monochrome displays are seen as having only one color.

Passive Display: A display that requires some ambient illuminance to produce displayed information. Some displays are reflective in nature (e.g., liquid crystal wristwatches) and require illumination on their surfaces to develop any contrast. Surface colors are another example.

Peripheral Vision: That part of the visual field that lies outside the fovea, or central vision area. Peripheral vision extends from approximately 90 degrees away from the point of fixation to about 1 or 2 degrees from the point of fixation. Peripheral vision is associated with reduced acuity, less color sensitivity, but greater luminance sensitivity under lower illumination conditions.

Phosphor: The typically rare earth material coated on the inside of a CRT or in an electroluminescent panel to provide luminance when activated by an electric current or an electron beam. Various phosphor mixtures result in the wavelengths of light.

Photopic Sensitivity: The relative sensitivity of the fovea of the eye to various wavelengths of light.

Pseudocolor: The use of colors in a scene that are not the same as the natural photopic vision of the same scene.

Raster-Scan Display: A display, typically on a CRT, that writes its information by modulating an electron beam that continuously scans its surface in the same pattern, usually left to right, top to bottom. Television displays are a typical example.

Saturation: The perceived purity of a color, as indicated by its departure from white (or gray). Saturation tends to correlate well with excitation purity.

Scotopic Sensitivity: The relative sensitivity of the peripheral retina to various wavelengths of light. Note that scotopic seeing does not result in the perception of colors, but only in shades of gray.

Specular Reflection: Specular reflection (literally, "mirror-like") consists of a single ray, reflected at an angle equal and opposite to its incident ray. That is, the three-dimensional angle created by the incident and reflected rays is bisected by the normal of the tangent plane at the point of incidence. This means that, for every viewpoint, there is a different pattern of reflected light mapped onto a surface (essentially, this is why specular reflection is expensive to compute). The intensity of specular reflection from any point on a dielectric surface varies nonlinearly with the angle of incidence (and reflection); it is brightest at grazing angles (100 percent at 90 degrees with respect to the normal) and least bright when the rays are perpendicular to the surface (4 percent, say, at 0 degrees). Specular refletion is generally assumed to be the color of the light source (the point in the environment) from which its incident ray emanates (see Diffuse Reflection).

Stroke-Written (Calligraphic) Display: A display on which information is written by electron beam modulation in whatever position and direction the information content requires, as opposed to a fixed pattern raster display.

Surface Color: Colors that are determined by light reflected from a surface. Examples are painted surfaces, printed maps, and photographs. Surface colors are determined by both the spectral reflectance of the surface and the composition of the ambient illuminance.

Wavelength of Light: The reciprocal of the frequency of light, assuming a wave theory of propagation. Visible wavelengths range from about 380 nanometers to about 760 nanometers, with greater sensitivity in the middle wavelengths, in accordance with the photopic sensitivity curve.

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